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Current perspective of brain-computer interfaces in arm exoskeletons

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Abstract. With the development of world scientific level, brain-computer interfaces (BCI) have become possible from the Arabian Nights. It has been achieved that humans do not need to act, but only use their thoughts to manipulate machines. Currently, many people are attempting to combine brain-computer interfaces with arm exoskeletons to assist humans who have lost mobility. This paper will interpret the literature on brain computer interface technology retrieved in the past five years, and summarize the current development and application of this technology in the world. Research has found that the literature on this technology has been increasing every year in recent years. The United States is in a leading position in this field, with research results and publications leading the world. At present, the development level of this technology is very considerable, and some people have already experienced the convenience brought by this technology. However, overall, the technology combining brain-computer interfaces with arm exoskeletons is not yet perfect. There are still many aspects that can be refined. This paper aims to provide a reference for further research and application in this field, and to provide useful references and ideas for workers and researchers in related fields.

Keywords: stroke, brain-computer interface, arm exoskeleton.

1. Introduction

The incidence of stroke-related paralysis has risen in recent years. Stroke refers to a sudden onset of neurological deficits with a localized area of the brain involved. It is associated with a high frequency, high mortality, and high disability rate. 80% of stroke patients will have some degree of functional impairment such as motor, cognitive, and speech. These conditions can seriously affect the lives of patients [1].

In 2019, the worldwide incidence of stroke was 12.2 million, with a total of 101 million individuals being stroke survivors. These strokes resulted in 6.55 million deaths and 143 million DALYs (Disability-Adjusted Life Year). Stroke ranks as the second primary cause of death globally, accounting for 11.6% of all deaths and the third highest cause of death and disability, contributing to 5.7% of total DALYs, following neonatal morbidity (7.3% DALYs) and ischemic heart disease (7.2% DALYs) [2].

These patients are very inconvenient in life. They don't have the ability to do things that ordinary people can easily do. But with the development of technology, it is no longer impossible for them to be able to live independently. Brain-computer interface, a technology that establishes a direct communication channel between external devices and the human brain. When this technology is combined with an arm exoskeleton, it could allow incapacitated patients to recover the ability to interact with the outside world by handling the device.

The current brain-computer interface system is mainly divided into three parts. The first part is the sensor responsible for collecting neural activity. The second and third parts are used to decode the recorded neural activity algorithm and the effector that performs the decoded action. Its main role is to capture and convert brain signals while generating high-precision commands to control the arm exoskeleton device in the patient's real environment.

Brain-computer interfaces offer a channel of communication between the brain and external devices that do not rely on muscle tissue. It is of great help to patients with motor nerve damage due to nerve damage or body amputation. Today, the way brain signals are captured and decoded is mainly non-invasive. Examples include functional near-infrared spectroscopy, fMRI (Functional magnetic resonance imaging) and EEG (Electroencephalogram) [3].

However, at present, the accuracy of brain-computer interface to capture and decode brain signals is low, so one of the current research focuses of this technology is to enhance the accuracy of brain signal capture and speed up decoding. In recent years, due to the remarkable achievements of brain-computer interfaces in clinical applications, both academia and the public have paid more and more attention to this technology.

2. Main body

2.1. Research progress

At present, the use of brain-computer interface technology to control the exoskeleton of the arm is becoming more and more common in clinical medicine. Humans can use ideas in their brains to exercise some control over the robot, such as panning or lifting their arms. Today's technology has also allowed people to control robots in greater detail than before. People can control the opening and closing of the fingers of the robotic arm. If people want, they can stretch one of their fingers. This also reflects the relative maturity of this technology.

2.1.1. Research progress on the combination of brain-computer interface technology and arm exoskeleton. At present, there are many types of arm exoskeletons used in clinical use. The hand rehabilitation part is mainly divided into single-finger, multi-finger, and full-finger.

In the brain-computer interface system part, there are also many types. At present, the most commonly used EEG-based brain-computer interface system. It has the characteristics of low cost, small size and non-invasive. The brain-computer interface system can sense the patient's motor rhythm through the EEG, and then decode it, so as to convert it into instructions to control the robotic arm. Research has indicated a direct and positive relationship between the rehabilitation outcomes of patients and the classification accuracy of the brain-computer interface arm exoskeleton [4]. To enhance the level of freedom associated with the brain-computer interface arm exoskeleton, it is imperative to enhance the ability of EEG for high classification accuracy. This can better help paralyzed patients and is of great significance to their recovery. As studies on signal extraction continue to progress, it has been discovered that the hemodynamic response obtained from the cerebral cortex using functional near-infrared spectroscopy is the most effective for brain-computer interface systems. When individuals intend to engage in physical exercise, the concentration of oxygenated hemoglobin in the supplementary motor area will increase, indicating a heightened cognitive motor demand within the brain during the initial phase of exercise [5]. Research on brain-computer interface systems using functional near-infrared spectroscopy has demonstrated that it is possible to extract and decode motor intentions for initiating and stopping motion by using functional near-infrared spectroscopy imaging [6].

2.1.2. Therapeutic effect of brain-computer interface technology combined with arm exoskeleton. From the current clinical treatment effect of this technology, it is not only conducive to the recovery of limb function, but also conducive to the recovery of the brain nervous system [7].

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In terms of limb restoration, the technology has great potential. Previous treatments did not have much restorative effect on finger stretching in stroke patients. The combination of brain-computer interface technology and arm exoskeleton can have a good recovery effect on the patient's fingers. And a large number of clinical data point out that it can also shorten the reaction time of patients [8]. Not only does it have a good recovery effect on the fingers, but the brain-computer interface technology also has a good recovery effect in other parts of the body. It can use continuous passive movements to help stroke patients regain wrist stretch function. And through biofeedback, it has a more direct impact on the recovery of muscle function. This will be a good way to improve the patient's self-care ability in life. This technique has great potential for hand correction in patients [9].

In terms of brain nerve recovery, the patient's recovery progress can be observed through electroencephalogram. EEG data can be used to assess neuronal damage and functional recovery through fractal size analysis. Andrei Agius Anastasi et al. proposed that the cerebral symmetry index can be used as a prognostic indicator for stroke rehabilitation. By observing the brain symmetry index, the asymmetric difference between the brain quantitative power of the damaged nerve region and the normal nerve region can be determined [10]. The brain-computer interface arm exoskeleton robot can through EEG feedback to guide the patient's paralyzed limb to perform its desired activity. At the same time, these activities can also feedback the stimulation of damaged neural networks, thereby promoting the connection of corresponding functional areas of the nerve center.

2.2. Application of BCI

Brain-computer interface technology plays a critical role in medical treatment, which includes the improvement, repair and replacement of brain functions. The integration of brain-computer interface technology can aid in the rehabilitation of stroke patients with motor dysfunction in their upper and lower limbs, as well as enhance neuroplasticity repair in the motor cortex.

At present, the scientific community believes that EEG-based brain-computer interface technology is a potential tool to restore the mobility of patients' upper limbs.

Broadly speaking, patterns of brain signal generation can be categorized into two types: EEG signals derived from motor imagery, and EEG signals derived from motor attempt. Both types of EEG signals can be detected and utilized to activate and operate external devices, like exoskeletal robots or functional electrical stimulation, in a closed-loop brain-computer interface system.

2.2.1. Functional electrical stimulation system and upper limb motor function recovery. Functional electrical stimulation causes the patient's muscles that have lost motor function to produce action potentials. Functional movement of paralyzed limbs can be achieved to improve the exercise capacity of stroke patients. Functional electrical stimulation can precisely detect the patient's motor intention, send commands to regulate the functional electrical stimulation device, execute the pre-set stimulation, and ultimately recover the limb's motor function as well as the hand's grasping function [11].

The use of EEG-based brain-computer interface technology to control functional electrical stimulation is believed to have a significant impact on the restoration of upper extremity motor function after a stroke [12]. It not only promotes the recovery of muscle function, but also matches brain signals, thereby promoting functional activity in distal muscles.

2.2.2. Exoskeleton robot with upper limb motor function recovery. Brain-computer interface technology combined with an arm exoskeleton is more common in clinical medicine than functional electrical stimulation. For stroke patients who lose mobility in their upper limbs, the arm exoskeleton can help them perform more than just some of the daily behaviors of life. It can also stimulate damaged motor nerves when the patient controls the exoskeleton of the arm with the brain, thereby increasing the likelihood of muscle function recovery. It is worth mentioning that the arm exoskeleton system supports patients to actively control arm exoskeleton movements according to their own ideas, rather than using pre-set movements. This can greatly improve patient motivation and treatment outcomes [13].

In the study of upper limb motor function in 14 stroke patients by Chen and Qing et al [14, 15]. One group of patients underwent 4 weeks, three times a week exoskeleton recovery training.The other group used only conventional rehabilitation.Studies have shown that patients who use the exoskeleton exercises of the arm have significantly better treatment outcomes than those who use conventional therapy.

3. Discussion

3.1. Research gaps

As an emerging technology in recent years, arm exoskeleton brain-computer interface technology has many research gaps. Next, this paper will list several aspects where the technology can be improved.

3.1.1. Accuracy of operational control. The arm exoskeleton needs to have high-precision and high-reliability operation control in motion control. At present, there are still certain difficulties in signal acquisition, processing, transmission and recognition to control the movement of the arm exoskeleton.

3.1.2. Equipment R&D and engineering. There is a need to improve the design, development and manufacture of existing arm exoskeleton devices. People want products that are more portable, soft, and comfortable to wear. At the same time, the maintenance, cost, durability and other aspects of the equipment still need to be further improved.

3.1.3. Authenticity of the therapeutic effect. The long-term therapeutic efficacy of arm exoskeleton brain-computer interface technology in clinical application is still unknown. Long-term follow-up or larger clinical trials are also needed for validation.

3.1.4. Improvement of brain signal capture methods. How to accurately and efficiently capture brain signals in the state of movement is still a major problem in current research. At present, there are still some limitations in the capture of brain signals, such as signal delay, noise, complexity, etc. The technology needs to be further refined and improved.

3.1.5. Improve electrode stability and signal quality. In the existing technology, there are still problems with the stability and signal quality of the electrode. New electrodes need to be investigated to improve their stability and signal quality.

3.1.6. In-depth study of rehabilitation mechanisms. It is also necessary to deeply study the rehabilitation mechanism of this technology and explore how it can achieve the recovery and improvement of limb movement through brain-computer interfaces to further promote its application and development.

3.2. Research directions

As an immature technology, there are many aspects that need to be improved in the future. Next, this article will list several future research directions of arm exoskeleton brain-computer interface technology.

3.2.1. Multimodal perception fusion technology for brain signals. Brain signal acquisition techniques primarily involve electroencephalogram and magnetic resonance imaging methods, among others. Given the unique attributes of brain signals, a comprehensive examination of temporal, spatial, and frequency domains is necessary. Therefore, multimodal perception fusion technology will become a crucial development direction of arm exoskeleton brain-computer interface technology in the future.

3.2.2. Neural network algorithms. Neural networks are an important part of artificial intelligence technology. Existing neural network algorithms have been applied in the field of arm exoskeleton brain-

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computer interface technology. However, because neural network algorithms require a lot of data and computing resources, their performance needs to be continuously optimized.

3.2.3. System stability and rehabilitation. Arm exoskeleton brain-computer interface technology needs to seamlessly combine human brain signals and mechanical control, so system stability and reliability are one of the key issues to realize this technology and need to be continuously improved.

3.2.4. Lightweight design of arm exoskeleton. The quality of the arm exoskeleton is one of the important issues for users when using it. How to reduce the weight of exoskeleton while ensuring the strength of exoskeleton structure will become one of the directions of follow-up research.

3.2.5. Individual customization needs. Neural signals and motor habits may differ between individuals. How to design and control the corresponding exoskeleton according to the needs of individuals is a direction of future research.

3.2.6. Solve force control and dynamics problems. The movement of the human arm is characterized by nonlinearity, time variability, and variable external loads. How to coordinate mechanical exoskeleton and human dynamics has become one of the problems that need to be solved.

3.2.7. Address security issues. The exoskeleton needs to meet safety needs to avoid accidents. Therefore, it is necessary to further study the safety of exoskeleton mechanisms and optimize their safety performance.

3.2.8. Continue to promote clinical translation. Although the technology has shown good prospects, there are many obstacles to its clinical translation. Therefore, it is necessary to continue to promote its clinical research and application and accelerate the speed of its clinical translation.

3.2.9. Reduce the cost of treatment. At present, the treatment cost of brain-computer interface arm exoskeleton technology is high, and the cost of treatment needs to be further reduced to improve the feasibility of its clinical application.

Arm exoskeleton brain-computer interface technology has attracted much attention in recent years. Research advances in this technique have led to the glimpse of its potential in helping stroke patients regain mobility.Some clinical studies have begun to study its application and efficacy in clinical medicine.

Despite ongoing research, the integration of this technology into clinical medicine remains in its developmental stages and further studies are warranted to support its broader implementation. Although the application of this technology in medicine is still in its infancy, based on the development of brain-computer interface technology and exoskeleton technology, it is believed that this technology will be widely used in clinical medicine in the future.

In summary, there are still many directions for further research and exploration of arm exoskeleton brain-computer interface technology. These studies will lead to the continuous development and improvement of technology, providing the basis for one day more intelligent and precise control.

4. Conclusion

Nowadays, the recovery effect of clinical treatment of limb motor function in stroke patients is relatively clear.The use of brain-computer interface arm exoskeleton technology in treatment has obvious advantages over conventional treatment. The brain-computer interface arm exoskeleton can help patients reshape their nerves to restore limb function from top to bottom.

In summary, brain-computer interface arm exoskeleton technology has become one of the hot areas of research and practice. While much progress has been made in the technology, there are still many challenges that need to be addressed. In the future, we can conduct research by improving the sensitivity

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and accuracy of algorithms, improving the flexibility of robotic arm structures, and expanding application scenarios. for more efficient, accurate, and intelligent control.

It is hoped that the review and analysis of this paper can provide useful reference and guiding ideas for the research and application in this field, and promote the further development and progress of this field.

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